General Comments:

This manuscript investigates the relationship between fire induced changes in ecosystem C and N stocks and climate in Sweden. The manuscript addresses relevant and important scientific questions related to the influence of climate on boreal forest fire C and N emissions and redistribution within an ecosystem. The novel dataset of field measurements along gradients in climate is valuable to the scientific community. However, the methods are unclear in several places, and the excessive use of abbreviations hinders both readability and comprehension. The
manuscript needs additional plots showing their raw data and model fits to aid in the interpretation of the methods and results. The relationships between boreal forest fire C and N emissions and precipitation, temperature, and soil moisture are a key finding in this study but are not strongly represented in the figures. Overall, the manuscript represents an important contribution to the scientific community, but it needs minor adjustments to make the overall presentation well-structured and clear.

(Response)

Thank you for the time taken to make these comments. They are both critical and helpful. In the following responses we aim to clarify the content and provide model fit diagrams where requested and possible. Our main results regard the pathways by which climate affects C and N losses by assessing several multiple regression models at a time. We therefore believe the path diagram figures to better represent these relationships than separately plotting individual multiple regression hyperplanes which would be difficult to interpret and also not be possible with more than 2 explanatory variables. All original data is provided as a supplement to the manuscript.

All author responses are labeled with the **(Response)** tag and colored blue to contrast the reviewer's original black (manuscript text) and red (reviewer comment) color coding.

Specific Comments:

Comment 1

Page 2, line 25: The predominant disturbance to this C balance is approximately centurial outbreaks of wildfire (Bond-Lamberty et al., 2007).

This sentence sounds like the author is suggesting the carbon balance in boreal forests is predominantly determined by wildfire outbreaks that occur once every century. While the return interval of fire in a local area of the boreal forest is centurial, boreal forest fires occur every year. I suggest re-wording this sentence for clarity.

(Response)

We agree that this is unclear, so we have modified the text to the following:

"The predominant disturbance to this C balance in the boreal region are yearly outbreaks of wildfires which reoccur in individual forest stands at the centurial timescale (Bond-Lamberty et al., 2007)."

Comment 2

Page 2, line 30: Along with a changing climate, these effects have the power to influence community structure and process rates shaping future forest C and N cycles on decadal to centurial timescales.

It is unclear what "process rates" the author is referring to.

(Response)

We agree this is vague, so we now modify the sentence to specifically refer to some key processes of interest:

"Along with a changing climate, these effects have the power to influence community structure and processes such as soil respiration and nutrient cycling which can shape future forest C and N cycles on decadal to centurial timescales (Johnstone et al., 2020; Mekonnen et al., 2019)."

Comment 3

Page 2, line 31: Changing patterns of temperature and precipitation in recent decades have caused increases in frequency, intensity and size of fires with further amplification predicted in the future.

The author needs to specify if they are referring to fires globally or regionally (Eurasian boreal forest fires).

(Response)

Agreed, the modified text is:

"…size of fires across the global boreal region with further amplification..."

Comment 4

Page 2, line 40: These factors dictate fuel availability, a highly temporal measure of the proportion of total fuel that is readily combustible.

I'm not sure what a "highly temporal measure" means. If the author is referring to the high temporal variability in available fuel, the phrase could be changed to "a highly temporally variable measure."

(Response)

Agreed, this could be worded better. It was meant that fuel availability is rapidly fluctuating in response to environmental conditions. Suggested text:

"These factors control fuel availability, a measure of the instantaneous proportion of total fuel that is readily combustible."

Comment 5

Page 2, line 45: Spatial arrangement of overstory fuel loads has also been shown to have a strong impact on fire severity and intensity and distinguishes the boreal wildfire regimes of the North American and Eurasian continents (Rogers et al., 2015).

The major difference in the boreal wildfire regimes in North America and Eurasia is the dominant tree species and corresponding ecosystem characteristics. The spatial arrangement of overstory fuels certainly contributes to crown fire behavior in the North American boreal forest, but the underlying reason for the difference is tree species. See Rogers et al., 2015.

(Response)

We would consider the underlying factors controlling fire behavior (e.g. presence/absence of crown fire) to be the physical properties of the trees and that species composition is just a tendency towards sets of those physical traits. Because our plots are almost completely pine dominant we only test for the effects on fire severity of physical variation instead of species variation. We can modify the text to acknowledge these different perspectives.

"Composition of tree species, with their associated fire adaptation strategies, has also been shown to have a strong impact on fire severity and intensity and distinguishes the boreal wildfire regimes of the North American and Eurasian continents (Rogers et al., 2015)."

Comment 6

Page 2, line 56: While total area burned may be evaluated through remote sensing (Ruiz et al., 2012), per area emissions are generally derived from labor intensive field sampling which are extrapolated to the larger scale either directly or through weighting by poorly constrained free parameters such as total fuel load (French et al., 2004; Soja et al., 2004). This field sampling has been regionally limited and biased towards a few high intensity burn complexes in North America which may in turn bias global emission estimates (van Leeuwen 60 et al., 2014).

The authors describe the commonly called "bottom-up" approach to calculate emissions, but fail to address alternative methods to calculate emissions, such as a "top-down" based approach (Ichoku and Ellison et al., 2014). Carbon emissions per unit area are calculated using a bottom-up approach as the product of fuel loading, combustion completeness and the carbon content of fuel. While some fire emissions inventories do rely on extrapolated field measurements to estimate one or more of the variables needed in the bottom-up approach, many rely on remote sensing observations (van der Werf et al., 2017; Veraverbeke et al., 2015).

(Response)

We acknowledge that different methods can be sorted into the broad categories of top-down and bottom-up. The manuscript has a dual role in comparing cross-regional C emission estimates as well as assessing drivers of local meter-scale C stock change in ecosystems. We retain focus on methodology that satisfies both of these research aims and this paragraph can be rephrased to (i) acknowledge and summarize larger-scale approaches and (ii) emphasize that spatial coverage of these fine scale measurements are lacking. Suggested text:

"Boreal C emissions due to a single wildfire can be calculated by multiplying total area burned by estimates of C emissions per area (French et al., 2004). While total area burned may be evaluated directly through remote sensing (Ruiz et al., 2012), per area C emissions are generally derived from labor intensive field sampling which is extrapolated to the larger scale either directly or through weighting by remotely sensed data (e.g. topography, vegetation cover) or poorly constrained free parameters such as total fuel load (French et al., 2004; Soja et al., 2004; van der Werf et al., 2017; Veraverbeke et al., 2015; Kaiseret al., 2012). This field sampling has been regionally limited and biased towards a few high intensity burn complexes in North America which may in turn bias global emission estimates (van Leeuwen et al., 2014; Akagi et al., 2011). For example, the Eurasian boreal region is dominated by relatively fire resistant overstory vegetation that avoids excessive heating by promoting lower intensity ground and surface fires than that in boreal North America, which is more prone to spread rapid flaming combustion throughout the canopy (Rogers et al., 2015; de Groot et al., 2013a). C loss in a group of Siberian boreal forest surface fires was found to be 0.88 kg C m^{-2}(Ivanova et al., 2011) which is about a quarter of what is typical in North American wildfire (3.3 kg C m^{-2}) (Boby et al., 2010; Walker et al., 2020) and about one fifth of an extreme wildfire in Fennoscandia (4.5 kg C m^{-2}) Granath et al. (2021). Although Eurasia contains over 70% of the boreal global land area (de Groot et al.,2013a) and about 50% (20 Mha yr^{-1}) of its yearly burnt area (Rogers et al., 2015), methodologies for estimating global and regional C emissions are severely lacking ground validation and meter scale assessments of drivers of C loss variability from this region (van der Werf et al., 2017; Kaiser et al., 2012)"

Comment 7

The methods section is missing a detailed description of fire severity in each of the 50 burnt plots. This omittance (and missing subsequent discussion) incumbers the interpretation of the results. The manuscript would also greatly benefit from the inclusion of an overview of the ecosystems sampled (by dominant tree species, for example) in each of the burnt plots. A histogram showing fire severity and ecosystem type could be helpful.

(Response)

Our ecosystems were mostly pine dominant, upland forests and can be considered a single ecosystem type. We agree this is essential background knowledge and have added an additional section in the results section to address your comment:

"3.1 Survey of burnt plot vegetation

The 50 burn plot overstories were largely pine dominant with a percentage of spruce stems between 25-50% in 5 plots, between 50-75% in 3 plots and 2 plots with greater than 75%. Birch stems were less than 25% in 44 plots and between 25-50% in 6 plots, of which only 1 of the 6 was spruce dominant. All plots showed visible charring of tree boles though only 3 plots had greater than 1% plot wide canopy blackening. These plots were pine dominant with 2 having less than 1% spruce while the other had 6 spruce of the 27 stems within the sampled area. Prefire aboveground overstory C and N were estimated as4.46±0.738 kg $m^{-2}$and 0.0385±0.00621 kg m^{-2}, respectively, with 5.31% of C (0.237±0.0321 kg m^{-2}) and 12.3%8of N (0.00474±0.000641 kg m^{-2}) coming from pine and spruce needles. The 50 burnt plots had a large percentage tree mortality (45.0±8.76%) compared to control (4.21±1.63%). Total C and N loss, as well as char layer mass, was not correlated to canopy browning, blackening nor increased mortality in burnt plots relative to control.

Understory coverage was reduced to 10.2±5.15% of its estimated prefire values. This laid bare the surface layer of charred material present in all plots. This layer was conglomerated and easily separable from lower layers and new litter additions which were mostly needles. Upon breaking apart the layer, it was found to be completely blackened throughout."

Comment 8

Page 4, line 100: Sentinel-2 infrared imagery taken during the time of fire assisted in delineating the exact locations of burnt plots by placing them where there had been a strong and consistent infrared signal that was well within the mapped final fire boundaries.

The method described here should be more quantitative. How was a "strong and consistent" infrared signal determined?

(Response)

True, this is unspecific. Our highest goal was to ensure good pair plot matching which we accomplished with a relatively objective and quantitative series of filters. We aimed to then have burnt plots close to the highest intensity pixels within the burn scar, for which we used the sentinel imagery. This was done to encourage sampling within the more developed parts of the fire rather than selecting plots only suffering heating along its periphery but not to quantiatvely compare active fire intensity across burnt plots. Suggested change:

"Sentinel-2 infrared imagery was used to locate planned burnt plots near pixels showing the highest intensity within the mapped final burn scar perimeter. This gave greater certainty the plots experienced a more developed fire effect rather than peripheral heating alone."

Comment 9

Page 4, line 112: Due to their documented effects on emissions, long and short term approximations of moisture were introduced as exogenous variables to models in order to test the ability of the study design to isolate variation in C and N stock losses to the effects of climate. Long term moisture was represented by the TEM used in plot selection while short term moisture balance used the Standardized Precipitation-Evapotranspiration Index (SPEI) over the period January to June 2018 (i.e. spei06 2018-06) to capture the desiccation process leading up to the fire season.

The methods described here are vague. What models were these variables introduced to? Is the goal to isolate variation in C and N stock losses caused by variability in climate? Why is long term moisture determined using only soil moisture, but short-term moisture is quantified using precipitation and evapotranspiration? Where did the SPEI data come from? The reference is Unclear.

(Response)

We have now modified the text to provide more specific explanations. Yes, one key goal is to isolate the variation of fire severity with climate. Long term moisture is actually approximated by the two separate parts, the topo-edaphic component (TEM), and the climate components (MAT and MAP), but there is no long term data on evapotranspiration. SPEI came from "SPEIbase", a global database of these values, now explicitly referenced. The following is suggested:

"Due to their documented effects on emissions, long and short term approximations of moisture were considered in this study. Long term moisture approximations were separated into a topo-edaphic component (TEM), and climatic component (MAP and MAT). Short term moisture was approximated over the first 6 months of 2018 using the Standardized Precipitation-Evapotranspiration Index (SPEI), which is calculated as the difference in precipitation and evapotranspiration in a given area, with data from the SPEIBase (Beguería et al., 2019) (i.e. spei06 2018-06) to capture the fuel desiccation process leading up to the fire season. SPEI was also compared to summer 2018 anomalies in temperature and precipitation, i.e. the difference in the 2018 June, July, and August average of these values from those during the same months averaged over the period from 1961 to 2017."

Comment 10

Page 5, line 123: Each compartment was further sorted by weight into characteristic features to form compartment compositional variables (CCVs) which were used in regression to test for relationships between compartment composition and the quantity and quality of fuel loading as well as C and N loss.

More detail is needed. What type of regression was performed? How were the relationships quantified? What metrics were used? What exactly are compartment compositional variables and how were they defined? What is meant by “quality of fuel loading”? The methodology described here is ambiguous.

(Response)

This paragraph was meant to be an introduction to the concepts with more specifics to follow. By quality of fuel loading it was meant bulk density, C_R, N_R, and CCVs.. But we agree the vagueness at this point in the text can cause confusion. We will keep it more introductory and direct the reader to later text for more details with the following:

“Each compartment was further sorted by weight into sets of characteristic components, here called compartment compositional variables~(CCVs), which are to be specifically defined for each compartment in the following sections.”

The metrics and regressions are explained at line 195, with the text becoming more clear with the following change:

“All CCVs described in this text were assessed for their direct correlations to C and N stock losses as well as their ability to improve the multiple regression models presented in the results section by using both original variables and their principal components produced by the PCA method in statsmodels.”

Comment 11

Page 5, line 137: Duff samples were taken near the mineral cores by excavating four soil volumes (at least 400 cm3 each) and trimming the mineral and moss/litter layers off the bottom and top of the volumes respectively, then recording the final dimensions of the residual duff sample. Duff and mineral soils were kept frozen until

portions were freeze dried for separate analysis. Moss/litter samples were collected at approximately equal intervals along the soil profile transects in a 553 cm3 steel container with attention to preservation of the natural in situ volume. Char was similarly collected in a 112 cm3 container. On the upper surface of the char layer were small portions of dry, unburnt material, much of which may be new additions of litter to the forest floor. This material was discarded from the char collection and was not included in stock estimates.

More information is needed on the sample collection protocol. How was the size of the duff and moss/litter sample collected determined? What, if any, steps were taken to avoid duff compaction? Was volume measured in situ?

(Response)

Duff:

We now describe this protocol in more detail. A large block of soil (~30 * 30 cm ground area) was carefully dug out with a long spade. The mineral and moss/litter layers were trimmed off. Then the block was trimmed down extensively to remove the edges (several cm) that were assumed to have greatest disturbance. The final sample was trimmed to right angles with very sharp scissors. This sample was then measured in millimeters with a ruler to record volume in situ and stored. We took relatively large duff samples in attempts to reduce sampling error. We tried several methods of duff sampling (including coring) and this one seemed to avoid compaction associated with more conventional coring approaches

Moss/litter:

We now describe this protocol in more detail. We walked across the two transects bisecting each plot cutting squares of moss/litter layer with a sharp knife. The squares were carefully laid into a container of known volume until that container was full. We could estimate from the soil profile measurements how many samples we would need to take when walking across the transect. We therefore knew how much samples should be spaced to spread across the plot area. The sample count was always at least 1 from each of the 4 plot quadrants.

Suggested change:

“Duff samples were taken near the mineral cores by excavating four soil volumes, trimming the mineral and moss/litter layers off the bottom and top of the volumes respectively, and then gently cutting right angles with sharp scissors to measure the 3 dimensions in millimeters~(collected samples were at least 400~cm^3 each). Duff and mineral soils were kept frozen until portions were freeze dried for separate analysis. Moss/litter samples were collected by cutting squares, with attention to preservation of the natural in situ volume, until filling a 553~cm^3 steel container. Char was similarly collected in a 112~cm^3 container. At least one sample each of moss/litter and char were acquired from each plot quadrant, though more were taken at equal spacing along a transect to fill the containers if the layer was thin.”

Comment 12

Page 6, line 156: In all plots, understory was clearly distinguished from overstory by pronounced height differences and samples were taken from control plots by cutting all non-moss, non-tree plant material at the surface of the soil from within four 40 x 40 cm2 patches. Patches were chosen for their representativeness of plant abundance and composition for the portion of the plot that was vegetated, which was always all non bare rock surface.

The methodology described here is not quantitative. What defined “pronounced height differences”? What metrics were used to select patches, or were the choices purely subjective?

(Response)

Pronounced height differences meant that the understory was less than a meter tall and the overstory greater than several meters tall without much vegetation heights in between. But this was vague and can be changed.

We practiced established methods of ‘random’ or stratified sampling but found the small sample size and area to often produce understory estimates that were clearly not representative of the whole plot. Our solution was to perform transects through the plot noting estimated percentage dominance and coverage of the plant functional groups and then placing the square cutting perimeter to represent this. We believe this method to be much more consistent at capturing functional group dominance across plots than attempts at random or stratified sampling with such a small portion of the total plot area.

Suggested change:

“Understory samples were taken from control plots by cutting all non-moss, non-tree plant material at the surface of the soil from within four 40×40 cm2 patches. To reduce sampling error due to small areal coverage of the plot the sample patches were chosen by performing transects through the entire plot noting visual estimates of coverage and proportions of plant functional groups (i.e. graminoids, forbs, shrubs, and pteridophytes) and selecting representative patches for the portion of the plot that was vegetated, which was always all non bare rock surface. These values were applied to a visual estimate of non bare rock surface area of the burnt plots as an approximation of its prefire understory coverage. CCVs for understory were determined by sorting the sampled understory plant material and measuring dried weights of the functional groups graminoid, forb, shrub, and pteridophyte."

Comment 13

Page 6, line 169: All samples were pulverized, except the mineral soil where only the fine earth fraction (< 2 mm) was analyzed (C and N content was set to 0 for the coarse fraction), and run through a Costech ECS4010 elemental analyzer to produce ratios of C and N weight to sample total weight (CR and NR respectively).

More information is needed on the elemental analyzer used to calculate the ratios. How were the samples prepared? What was the measurement protocol? How was the instrument calibrated? Also, the abbreviations are confusing. Perhaps consider changing to carbon (nitrogen) mass percentage or something similar.

(Response)

The samples were pulverized and placed in tin capsules. They were then combusted and separated using gas chromatography and then measured separately for their total amount using their thermal conductivity all within the Costech ECS 4010 elemental analyzer

Suggested change:

"All samples were pulverized, except the mineral soil where only the fine earth fraction (<2 mm) was analyzed (C and N content was set to 0 for the coarse fraction) and packed in tin capsules. The capsules were combusted in a Costech ECS 4010 elemental analyzer, equipped with a 2 m packed chromatographic column for gas separation, to produce ratios of C and N weight to sample total weight (CR and NR respectively). After every 10 samples, standardized acetanilide (from the company Elemental Microanalysis, Okehampton, United Kingdom) was run to calibrate the machine within 1%."

We would like to reserve the use of percentages as a colloquialism while leaving key variables as they appear in calculation to maintain consistency.

Comment 14

Page 6, line 185: Changes between control and burnt plots were first calculated by subtracting control plot values of a variable from those of its burnt pair thereby forming a single distribution of 50 elements for statistical testing.

This sentence should be re-worded for clarity. Or, an equation could be introduced here using the delta (D) notation to indicate change. Additionally, the author does not state exactly what variables are compared between control and burnt plots in this sentence.

(Response)

Suggested change: “Unless otherwise noted, all measured changes between control and burnt plots..”

Comment 15

Page 7, line 192: Simple regression was performed using the stats.linregress method from SciPy

(Virtanen et al., 2020) providing significance (p), correlation (r), and slope (b). Multiple regression was carried out with the OLS method in the Python 3 statsmodels package (Seabold and Perktold, 2010) with models evaluated in order of increasing Akaike information criterion. Standardized regression coefficients (B) were produced by normalizing all variables (converting to z scores) before regression. CCVs were assessed in regression models both using original variables and their principal components produced by the PCA method in statsmodels.

What type of regression was performed? Linear, least squares, orthogonal distance? OLS needs

to be defined. It is unclear what is meant by CCVs were assessed in regression models. What were they assessed for? Akaike information criterion needs a reference.

(Response)

Ordinary least squares regression was used. OLS is the name of the method from the statsmodels package; it's just a label for computer code rather than an acronym or generic procedure. The CCVs were checked for correlation to C and N losses as well as to improve regression analyses in the results section (to no avail). AIC can be referenced. Suggested changes:

“All regression analyses used the ordinary least squares approach to estimate a function for a single response variable based on linear combinations of the predictor variables and an intercept term. Simple regression was performed using the stats.linregress method from SciPy~(Virtanen et al., 2020) providing significance~(p), correlation~(r), and slope~(b). Multiple regression was carried out with the OLS method in the Python~3 statsmodels package~(Seabold and Perktold, 2010) with models evaluated in order of increasing Akaike information criterion~(Akaike, 1974). Standardized regression coefficients~(β) were produced by normalizing all variables~(i.e. converting to z scores) before regression. All CCVs described in this text were assessed for their direct correlations to C and N stock losses as well as their ability to improve the regression models presented in the results sections by using both original variables and their principal components produced by the PCA method in statsmodels.”

Comment 16

Page 7, line 212: The largest total loss of C in burnt plot compartments due to fire was from the duff layer (Fig. 2a) About three quarters of the moss/litter C was removed from burnt plots, comprising about half as much as the total amount of C that was removed from the duff layer. Understory C removal due to fire was near complete, but had a relatively small contribution to overall elemental stocks and their changes. Of the average amount of C lost from these three compartments, 54.3% was found in the averaged char layer and only 0.19% in the increased C found in burnt plot mineral layers which themselves had no significant overall change in C between control and burnt plots.

This sentence is confusing. Does this mean 54.3% of the C lost from duff, moss/litter and understory was redistributed into the char layer? Was the rest emitted to the atmosphere?

(Response)

We rephrase to state that an “equivalent amount” was found in the char, to avoid misleading the reader to believe we have evidence of what proportions of each compartment’s C are going where.

"Char layer C averaged across the 50 burnt plots was equivalent to 54.3% of the average C lost due to fire from the combined understory and organic compartments."

Comment 17

Page 7, line 204: Section 3.1

This section is difficult to follow. Maybe consider adding subsections for clarity and readability.

(Response)

Agreed, we now give a subsubsection for each paragraph.

Comment 18

Section 3 Results:

It would be helpful to see how these results vary as a function of ecosystem type to extrapolate the results to other boreal regions.

(Response)

The plots occur within a set of fairly homogenous, upland, pine-dominant Fennoscandian boreal forest. We were not able to identify any factors separating the ecosystem into types that are subject to different fire patterns (except what we display continuously as opposed to categorically, e.g. organic layer depth, climate). We agree it is very helpful to have more background on the ecosystems (especially dominant overstory) and have included that in the added results section concerning vegetation (also included a few comments above).

"3.1 Survey of burnt plot vegetation

The 50 burn plot overstories were largely pine dominant with a percentage of spruce stems between 25-50% in 5 plots, between 50-75% in 3 plots and 2 plots with greater than 75%. Birch stems were less than 25% in 44 plots and between 25-50% in 6 plots, of which only 1 of the 6 was spruce dominant. All plots showed visible charring of tree boles though only 3 plots had greater than 1% plot wide canopy blackening. These plots were pine dominant with 2 having less than 1% spruce while the other had 6 spruce of the 27 stems within the sampled area. Prefire aboveground overstory C and N were estimated as4.46±0.738 kg $m^{-2}$and 0.0385±0.00621 kg m^{-2}, respectively, with 5.31% of C (0.237±0.0321 kg m^{-2}) and 12.3%8of N (0.00474±0.000641 kg m^{-2}) coming from pine and spruce needles. The 50 burnt plots had a large percentage tree mortality (45.0±8.76%) compared to control (4.21±1.63%). Total C and N loss, as well as char layer mass, was not correlated to canopy browning, blackening nor increased mortality in burnt plots relative to control.

Understory coverage was reduced to 10.2±5.15% of its estimated prefire values. This laid bare the surface layer of charred material present in all plots. This layer was conglomerated and easily separable from lower layers and new litter additions which were mostly needles. Upon breaking apart the layer, it was found to be completely blackened throughout."

(Comment)

The authors mention adding variables to models to improve fits in numerous places in the results, but do not adequately describe the models or variable combinations in the methods.

(Response)

True. Though hundreds of models were tested and it would be impractical to list them all. We can rephrase to more clearly separate the CCVs and "fuel arrangement" factors from the results by stating that they were used to test for their direct correlations to C and N loss as well as a supplement in *all* presented regressions for their ability to improve them.

Line 197: "All CCVs described in this text were assessed for their direct correlations to C and N stock losses as well as their ability to improve the multiple regression models presented in the results section by using both original variables and their principal components produced by the PCA method in statsmodels. The effects of C and N stock arrangement amongst forest compartments were tested by entering the per plot ratios of the sums of different combinations of compartment C and N stocks into regression analyses both directly and to improve all models presented in the results section."

(Comment)

The results focus primarily on the redistribution of C and N into different forest pools (or compartments). Perhaps the title of the manuscript should be changed to reflect this focus?

We agree this is a central focus but we opt to use the word "restructured" since it can be defined specifically to refer to proportional distribution of total amounts across compartments as well as changing bulk density and weight concentrations. This can be made clear by splitting hypothesis 1 (Line 80) into two parts:

"1. Fire significantly reduced C and N stocks across forest compartments

2. Fire restructured organic layer C and N stocks by increasing overall bulk density and adjusting their weight concentrations across residual compartments and a newly formed pyrogenic layer."

The title has been revised to the following: "Climatic Variation Drives Wildfire Loss and Restructuring of Carbon and Nitrogen in Boreal Forests".

Comment 19

Page 8, line 235: To quantify the relative contribution of fire induced changes in organic layer depth, bulk density and elemental weight ratios on organic layer C and N losses they were linearly combined and entered into multiple regression.

More information is needed to describe the multiple regression. "entered into" is unclear. Do the authors mean they performed a multiple regression on the linearly combined variables? What is meant by linearly combined? Added? The following discussion concerning the combination of variables in an attempt to explain changes in C and N stocks is unclear. Plots showing the raw data and model fits would be tremendously helpful in understanding this Section.

(Response)

Linearly combined is a specific, strictly defined term meaning they form an expression where they are each multiplied by a constant (which is the beta value to be estimated in regression) and then added together.

Per plot-pair C (and N) losses are calculated by the equation

$$\text{Loss} = -1 * [\text{BurntPlot}(\text{BulkDensity} * \text{Depth} * C_R) - \text{ControlPlot}(\text{BulkDensity} * \text{Depth} * C_R)]$$

which is not a linear combination of the individual variables but of their burn-control separated products. Here linear regression is used as a convenient way for estimating the contributions of the variation of the change (i.e. plot paired burn minus control) of these variables on C and N losses at the sacrifice of model fit. A linear model was constructed like this

$$Loss = -1 * [\beta_1 * \Delta BulkDensity + \beta_2 * \Delta Depth + \beta_3 * \Delta C_R + \beta_0]$$

with the variables converted to z scores. The β estimates then represent the relative influence of the fire induced change of the variables on the stock loss. This was done to show that changes to each of the variables due to fire have a nearly equivalent influence on losses of C. This is important knowledge because it is sometimes assumed that change in depth is the strongest signifier of C change or that C_R can be approximated with reference data and the same value can be applied to both control and burn plot stock estimates. It also can support explanations or open up questions, such as to ask why total N is lesser influenced by bulk density and elemental concentration than C.

The R^2 value is given just to show that the linear approximation of the ideal relation is not poorly fitting. Discrepancy from 1 is just from purposely using an inferior model and likely not providing any intuitive information. Plotting would require a hyperplane in 4 dimensions, which is infeasible, and deviation from a perfect fit would come only from the noise due to the inferior model selection. Therefore we opt to provide only the valuable β values.

Suggested change:

"3.2.6 Statistical contribution of measured changes to C and N losses

To quantify the relative statistical contributions of the variation of fire induced changes in organic layer depth, bulk density and elemental weight ratios they were used as predictor variables in multiple regression to explain organic layer C and N losses. The C loss regression produced a model of fit of R^2= 0.865 and standardized regression coefficients for changes in depth (β= -0.670), bulk density (β= -0.633) and C_R(β= -0.583). N loss produced a model fit of R^2 = 0.777 and coefficients for loss of depth (β= -0.599), bulk density (β= -0.398) and N_R (β= -0.382). This shows that changes of these variables due to fire all had a strong effect on C and N stock loss estimates. Measured change in organic layer depth is the strongest determinant of losses of N. However, for C bulk density and elemental weight ratios are nearly as important as depth."

Comment 20

Section 3.3

While the p values are significant, the correlations are poor. The author should more fully address the low correlations.

(Response)

The correlations were discussed in manuscript at the following lines:

Line 265 - MAT is confounding MAP to explain C loss

Line 295 - MAT confounds or influences fire weather patterns that determine char production

Line 353 - MAP is mediated by fuel build up.

The strength of the effect fuel build up itself is then discussed with a paragraph added at line 398:

“Fuel loading has been found to have a varied strength of control on boreal wildfire C loss globally. This study found total C loss to relate to belowground C in simple regression with an R2 of 0.494 and to aboveground C insignificantly. These results are within the broad range found in Walker et al. (2020) where total C losses across 4 North American boreal ecoregions were directly related to prefire belowground C with R^2 values of 0.024 (insignificant), 0.07, 0.051, and 0.579 and to respective prefire aboveground C with 0.229, 0.005 (insignificant), 0.101, and 0.336. Little is known what factors dictate the strength of these controls and what portions of unexplained variation can be attributed to either additional measurable factors, methodological error or stochastic fire processes for a particular wildfire event. This study attempted to address these issues by testing many measurable ecosystem properties across several ecosystem C storage compartments finding the organic layer C stock along with its climate related prefire fuel conditioning and combustion susceptibility to be most predictive of C loss (Fig. 4a). These trends were demonstrated using a consistent methodology that incorporates high replication and broad spatial coverage, thereby offering better constraints on remaining unexplained variation across the region than might be provided by sampling a single burn scar or comparing results from different study designs.”

Comment 21

Page 9 line 266: MAT was negatively quadratically related to losses in CO (p = 0.008, R2 = 0.186)

and NO (p = 0.002, R2 = 0.233), both peaking near 4°C.

There is no clear description of applying a quadratic model fit to the variables in the methods.

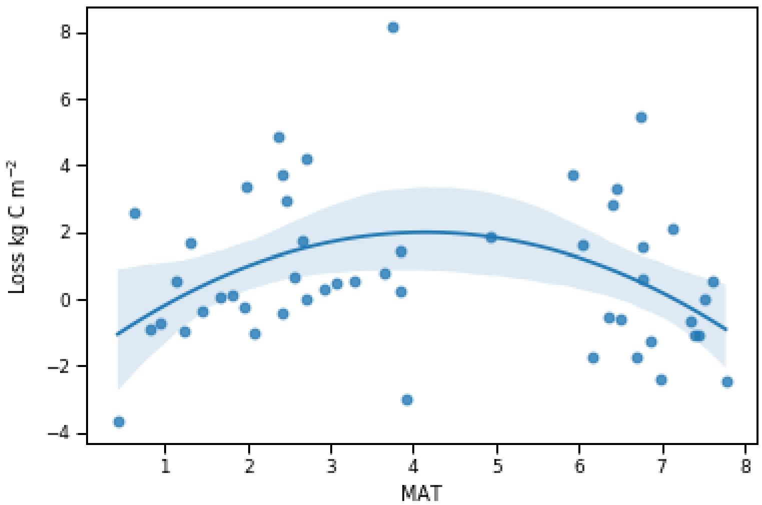
Again, plots of the data and model fits would be extremely helpful.

(Response)

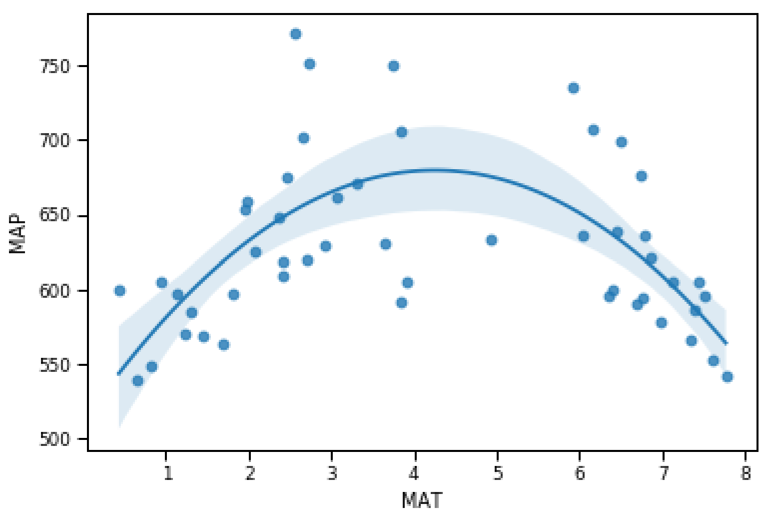
The methods section explained linear multiple regression (Line 193) which was used with a quadratic fit for MAT and MAT^2 variables in the form

$Loss = b_1 * MAT^2 + b_2 * MAT + b_0$

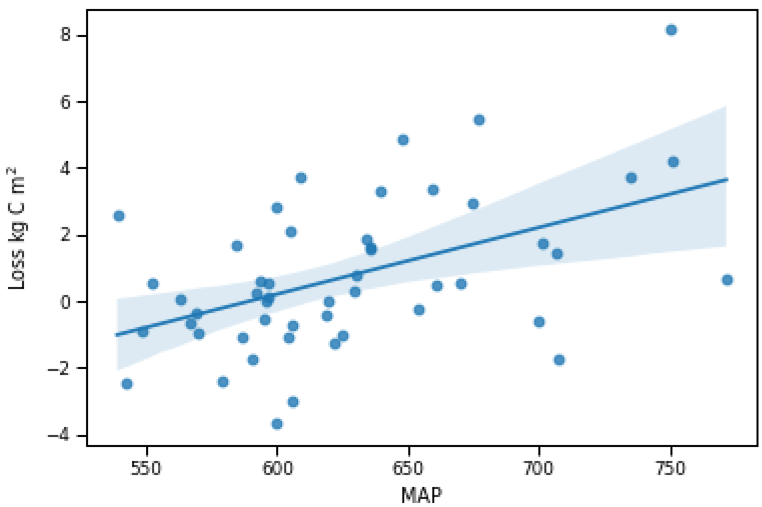
where b_1 was found to be negative meaning the hyperplane equation can be represented as a plot in reduced dimensions as an upside down parabola peaking at 4°C. The model fit had low R^2 and was determined to be due to confounding with MAP (Line 267). Here is the lower dimensional representation of the model:

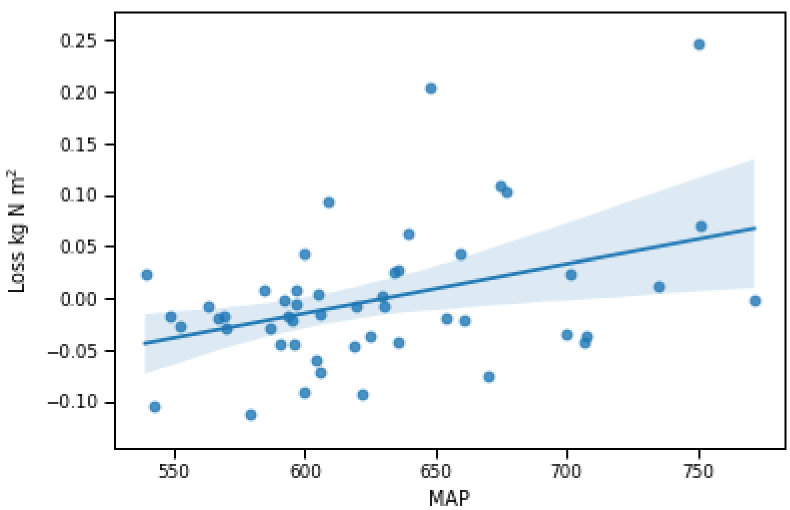


The relation of MAT to MAP:



And the univariate regressions for MAP vs C or N loss:





Suggested change: “In multiple regression, MAT and MAT^2 formed a negative quadratic relation to losses in C”

Comment 22

Section 4.3

Has the transport of N via aerosol emissions from nearby fires or even re-distribution within the same area due to a fire been considered?

(Response)

Yes, we considered this possibility and now explicitly acknowledge it in the manuscript (Line 319).

"However, material may have been added from downward movement of overstory components during the time of fire or deposition of aerosols coming from outside the plot. By selecting plots well within the final fire perimeter it was assumed that incoming and outgoing aerosols during the fire would be approximately equal and that extended aerosol deposition from more remote sources would deposit equally on control and burnt plots."

Technical Corrections

Suggested changes in red.

Page 1, line 22: The balance of C transferred between atmospheric and terrestrial stocks on the a yearly timescale is dictated by rates of terrestrial net primary production and respiration, which are strongly controlled by temperature, moisture and nitrogen (N) availability.

(Response)

accepted

Page 2, line 29: Further, bioavailability of energy sources and nutrients is substantially affected as elements such as C and N are lost, and their chemical structure is altered by heating.

(Response)

accepted

Page 2, line 30: Along with a changing climate, these effects have the power to influence community structure and process rates, thereby shaping future forest C and N cycles on decadal to centurial timescales.

(Response)

Suggested:

"Along with a changing climate, these effects have the power to influence community structure and processes such as soil respiration and nutrient cycling which can shape future forest C and N cycles on decadal to centurial timescales"

Page 2, line 38: However, in order for this fuel to be available to ignite and propagate sustain fire, it must be sufficiently dried and spatially arranged to be susceptible amenable to high heat and oxygen exposure during an active fire.

(Response)

accepted

Page 2, line 40: Therefore, boreal wildfire models often incorporate short term fire weather variables (e.g. drought indices, temperature, wind speed, relative humidity) and separate as well as separate fuel loads into distinct compartments, such as surface litter, to address the temporal variability in fuel availability. Fuel structure which influences ignition and rate of spread, and the more compactly arranged layers below which act as a heat reservoir that supports extending smoldering combustion over days to weeks.

(Response)

Suggested:

"Therefore, boreal wildfire models often incorporate short term fire weather variables (e.g. drought indices, temperature, wind speed, relative humidity) and separate soil fuel loads into distinct compartments such as surface litter, which influences ignition and rate of spread, and the more compactly arranged layers below, which act as a heat reservoir that supports extending smoldering over days to weeks (de Groot et al., 2003; Van Wagner, 1987; Rabin et al., 2017; Kasischkeet al., 2005; Wiggins et al., 2020)."

Page 2, line 49: Fuel chemical composition chemistry, arrangement, moisture content, applied heat and oxygen availability in turn have all been related to the efficiency of the combustion reaction during fire and therefore emission chemistry and the charring of remaining nonvolatilized fuel.

Suggest adding reference: Lobert, J.M. and Warnatz, J., 1993. Emissions from the combustion process in vegetation. Fire in the Environment, 13, pp.15-37.

(Response)

Thank you for the reference suggested. It has been added.

Page 3, line 60: For example, the Eurasian boreal region is dominated by relatively fire resistant vegetation that promotes lower intensity fire (Rogers et al., 2015; de Groot et al., 2013a) and C loss (0.88 kgC/m2) (Ivanovaet al., 2011) than that in typical (Walker et al., 2020) North American wildfire (3.3 kgC/m2) (Boby et al., 2010; Walker et al., 2020).

Are the C loss estimates an average over many years? More description is needed.

(Response)

We have now revised the text to clarify this:

"For example, the Eurasian boreal region is dominated by relatively fire resistant vegetation that promotes lower intensity fire than that in boreal North America (Rogers et al., 2015;de Groot et al., 2013a). C loss due to a group of Siberian fires was found to be 0.88 kgC/m2(Ivanova et al., 2011) which is about a quarter of what is typical in North American wildfire (3.3 kgC/m2) (Boby et al., 2010; Walker et al., 2020)..."

Page 3, line 64: Although Though Eurasia contains over 70% of the boreal global land area (de Groot et al., 2013a), and about 50% (20 Mha/yr) of its yearly burnt area (Rogers et al., 2015), wildfire emissions from this region are severely under sampled in the field (van Leeuwen et al., 2014).

(Response)

accepted

(Comment)

Missing many references. Suggest adding the following:

Akagi, S.K., Yokelson, R.J., Wiedinmyer, C., Alvarado, M.J., Reid, J.S., Karl, T., Crounse, J.D. and

Wennberg, P.O., 2011. Emission factors for open and domestic biomass burning for use in atmospheric models. Atmospheric Chemistry and Physics, 11(9), pp.4039-4072.

Andreae MO. Emission of trace gases and aerosols from biomass burning–an updated assessment. Atmospheric Chemistry and Physics. 2019 Jul 4;19(13):8523-46.

Andreae MO, Merlet P. Emission of trace gases and aerosols from biomass burning. Global biogeochemical cycles. 2001 Dec;15(4):955-66.

De Groot, W.J., Pritchard, J.M. and Lynham, T.J., 2009. Forest floor fuel consumption and carbon emissions in Canadian boreal forest fires. Canadian Journal of Forest Research, 39(2), pp.367-382.

Potter, C., 2018. Ecosystem carbon emissions from 2015 forest fires in interior Alaska. Carbon balance and management, 13(1), pp.1-10.

Rogers, B.M., Veraverbeke, S., Azzari, G., Czimczik, C.I., Holden, S.R., Mouteva, G.O., Sedano, F.,

Treseder, K.K. and Randerson, J.T., 2014. Quantifying fire-wide carbon emissions in interior Alaska using field measurements and Landsat imagery. Journal of Geophysical Research: Biogeosciences, 119(8), pp.1608-1629.

(Response)

Great, these have all been read and incorporated where and if appropriate in the manuscript.

Page 3, line 75: Analysis intended to The goal of this study is to distinguish the effects of climate

on fire induced changes in C and N stocks with direct, fine scale measurements and little loss of generality thereby providing insight into both local processes and valuable, globally comparable data from an under sampled region.

Not sure what is meant by "little loss of generality."

(Response)

It was meant that the methods weren't intended to be so specific that the results could be considered ad hoc.

suggested change:

"The goal of this study is to distinguish the effects of climate on fire induced changes in C and N stocks from an under sampled region with direct, fine scale measurements that both provide insight into local processes and allow for global comparison."

Page 3, Line 88: 50 burnt plots were selected from a pool of 325 fires identified during the summer 2018 period which were mapped from remotely sensed data and provided by the Swedish Forest Agency (Skogsstyrelsen).

And Page 4, Line 94: The first constraints on site selection were to avoid wetland or steeply sloping areas using prefire, topo-edaphic derived soil moisture data (TEM) provided by the Swedish Environmental Protection Agency (Naturvårdsverket) (Naturvårdsverket, 2018) and elevation and slope data provided within the ArcGIS software environment.

And Page 4, Line 110.

Is the reference referring to a location? Please clarify.

(Response)

These are the equivalent Swedish names for the agencies. We recognize the confusion and they will be removed.

Page 4, line 90: Remote sensed data was taken as the average pixel value within a 20 m diameter circle centered on the plot with GIS analysis utilizing QGIS (QGIS Development Team, 2019), ArcGIS (Esri Inc., 2019) and the pandas Python 3 package (Wes McKinney, 2010).

The authors describe their methodology for using remotely sensed data before describing exactly what that data is and where it is from. Suggest reorganizing this section.

(Response)

We have revised the text to first present the data and source, then the methodology: :

“50 burnt plots were selected from a pool of 325 fires identified during the summer 2018 period which were mapped from Sentinel-2 infrared data and provided by the Swedish Forest Agency. Each 20×20 m2plot was located within distinct burn scars (greater than 2 km separation) to reduce potential for pseudoreplication or spatial autocorrelation (Bataineh et al., 2006) and allow for increased spread across the climate gradients (Schweiger et al., 2016). Constraints were placed on plot selection using spatial data within the QGIS (QGIS Development Team, 2019) and ArcGIS (Esri Inc., 2019) software environments. Plot wide values for raster data were taken as the average pixel value within a 20 m diameter circle centered on the plot. The first constraints…:

Page 4, line 100: Sentinel-2 infrared imagery taken during the time of fire was used to delineate assisted in delineating the exact locations of burnt plots by determining placing them where there had been a strong and consistent infrared signal existed that was well within the mapped final fire perimeter boundaries.

(Response)

accepted

Page 4, line 121: The compartments included These were the four soil layers, of mineral, duff, moss/litter and char, as well as the two aboveground compartments, of the understory and overstory vegetation.

(Response)

accepted

Page 4, line 122: The organic layer was defined as the considered the grouping of the duff, moss/litter and char layers grouped together.

(Response)

accepted

Page 5, line 146: If a fallen tree was charred only on its lower (in standing orientation) portions, it was deemed standing during fire ignition and its measurements were included if its base was within plot boundaries.

(Response)

accepted

Page 5, line 153: Only bole diameters from the burnt plots were used to investigate When testing the influence of overstory vegetation on C and N loss, while bole diameters from adjacent control plots were ignored. bole diameters from the burnt plots were used and not the adjacent control. C and N stock estimates for overstory were not included in this analysis, and the measurements were only used to assess its role in controlling C and N stocks in all other compartments.

(Response)

accepted

Page 6, line 165: CCVs for these two layers were calculated as the sum of the formed by weights
of these coarse and fine fractions.

(Response)

Suggested change:

"The weights of the coarse and fine fractions formed a pair of CCVs for each of the layers."

Page 6, line 175: Data was stored in comma-separated value files with minimal redundancy. Calculations were performed with custom written Python 3 code using the pandas library. The measurable properties used in C and N stock calculations within soil compartments are the depth, bulk density and CR or NR.

I suggest deleting the first two sentences in this paragraph, as they are unnecessary. Throughout the manuscript, "stock calculations" need to be defined as C and/or N stocks. Otherwise, it is difficult to understand what is meant by "stock calculations."

(Response)

accepted

Page 7, line 187: These distributions were approximated as normal and unless otherwise noted,

and all confidence intervals were constructed at the 95% level using the formula

(Response)

Suggested change:

“These distributions were approximated as normal and all confidence intervals were constructed at the 95% level, unless otherwise noted, using the formula”

Page 7, line 204: C and N stock losses and rearrangement.

Suggest changing the word “rearrangement” to “redistribution” throughout the manuscript.

(Response)

We opt to use the word “restructured” since it can be defined specifically to refer to proportional distribution of total amounts across compartments as well as changing bulk density and weight concentrations. This can be made clear by splitting hypothesis 1 (Line 80) into two parts:

1. Fire significantly reduced C and N stocks across forest compartments

2. Fire restructured organic layer C and N stocks by increasing overall bulk density and adjusting their weight concentrations across residual compartments and a newly formed pyrogenic layer.

Page 10, line 315 The char layer was likely largely produced by fire interacting with the understory and moss/litter layer, however averaged char layer C and N stocks were greater than losses from the two layers combined suggesting there were also large contributions also from the duff layer.

(Response)

accepted

Page 11, line 318: Because the char layer was conglomerated and completely blackened, it is unlikely that material was incorporated postfire.

(Response)

accepted

Page 11, line 327: N losses in non-boreal forests have been related to fire fuel temperature during time of fire with lower intensity fires transferring a greater proportion of pools of organic N into soil ammonium and nitrate rather than removing N in gaseous forms (Neary et al., 1999).

(Response)

accepted

Page 11, line 331: Therefore, the N cycle in boreal systems may be highly dependent on active fire properties, fuel type and resulting fuel transformation, and the greater N losses in Alaska compared to Eurasia could be explained by its dissimilar fuel and the characteristically more intense crown fires across the North American boreal zone (de Groot et al., 2013a; Wooster and Zhang, 2004).

(Response)

accepted

Page 11, line 359: This direct effect was largely mediated by the incorporation of measures of fire-induced fuel transformation into the models, i.e. production of char layer C or N.

(Response)

addition of “the” accepted